ISSN: 2458-8989

Natural and Engineering Sciences

NESciences, 2025, 10 (2): 540-551 doi: 10.28978/nesciences.1758862

The Role of Biotechnology in Animal Nutrition

Ali. Abdalwahab. M. Al-Kuhla [1*]

[1*] Lecturer, Department of Veterinary Public Health, College of Veterinary Medicine, University of Mosul, Iraq.
E-mail: aliaug1976@uomosul.edu.iq

Abstract

This review supplies an overview of the key role played by modern biotechnology in the advancement of animal nutrition. With the global demand for animal products rising, new strategies are needed to enhance feed efficiency, animal health, and the sustainability of animal production. The review highlights how biotechnological interventions, including genetic modification (GM) and precision gene-editing technologies like CRISPR, address challenges posed by traditional feeding systems such as nutrient digestibility, anti-nutritional factors, and environmental sustainability. The paper addresses the application of genetic engineering in consolidate the nutritional amount of feed crops, utilization of improved enzymes, and the design of next-generation probiotics and prebiotics to re-model the gut microbiota. It also discusses new methods of manipulating the rumen microbiome for greater efficiency and methane synthesis reduction. The review concludes that these advances have the potential to get better nutrient employment, lower fodder expenses, minimize the environmental footprint of animal agriculture, and decrease reliance on antibiotic growth promoters. Moreover, the review shines a light on the complex social, economic, and ethical considerations that accompany these technologies, particularly with emerging gene-editing technologies that demand new regulatory frameworks and public debate. It outlines important areas of future research, including long-term ecological effects studies and further understanding of host-microbiome interactions. The abstract calls for continued research to advance these technologies, their efficacy and safety, and public acceptance to maximize their complete potential for sustainable animal production.

Keywords:

Biotechnology, animal feed, genetic modification, gene editing, crispr, enzymes, probiotics, rumen microbiota, sustainable agriculture.

Article history:

Received: 27/04/2025, Revised: 29/05/2025, Accepted: 19/07/2025, Available online: 30/08/2025

Corresponding Author: Ali. Abdalwahab. M. Al-Kuhla, E-mail: aliaug1976@uomosul.edu.iq

Introduction

Animal nutrition is a pillar of the world agricultural sector, having a direct impact on the productivity, health, and overall well-being of livestock. Its importance is realized through its direct role in the effective production of essential animal offspring like milk, meat and eggs that are required to provide global food security and sustain healthy rural economies. With the population of the world on the rise, the demand for good animal protein is likely to increase exponentially, placing the livestock industry under unprecedented pressure to enhance sustainability as well as productivity in an environmentally friendly manner (Canton, 2021).

Despite their popularity, conventional animal feeding systems are now facing serious problems that cast doubt over the long-term sustainability of these systems. From an economic standpoint, animal producers are typically exposed to the erratic availability and volatile prices of conventional feedstuffs such as maize and soybean meal. Moreover, a large proportion of plant-based feed ingredients contain un -nutritional agent (ANFs) such as phytates and non-starch polysaccharides (NSPs) which can inhibit digestion and reduce nutrient absorption. Environmentally, animal production is a major cause of global problems, mainly via the emission of extremely powerful greenhouse gases like methane by ruminant animals and the release of surplus nitrogen and phosphorus into the environment, leading to soil and water pollution (Khan et al., 2024).Secondly, the global shift towards banning antibiotic growth promoters (AGPs) in a bid to minimize antimicrobial resistance creates an acute necessity for effective alternatives to promoting gastrointestinal health and disease protection (Mehrani et al., 2016).

Biotechnology is a dynamic, rapidly evolving field able to generate countless new solutions to these complex problems. Beyond the initial generation of genetic transformation, new breakthroughs in precision gene-editing technologies (e.g., CRISPR-Cas9) enable targeted improvement of feed crops with unprecedented accuracy. In addition to these gene technologies, other significant developments in the industry include the creation of newer and improved feed enzymes (Urgessa et al., 2024), next-generation probiotics with enhanced functionality (Martin, 2024), and novel strategies for governing the complicated rumen microbiome to deliver environmental and productivity benefits (Said et al., 2020). Collectively, these biotechnology developments equate to a shift in animal nutrition towards more precise, efficient, and sustainable approaches.

This review will provide a general and critical abstract of the central part of new biotechnology in animal nutrition. Specifically, it is examining key biotechnological interventions, including mature genetically engineered feedstuffs, novel gene-editing technologies, novel enzymes, and microbial additives such as probiotics and prebiotics (Kapoor et al., 2025, Menon & Joshi, 2024). The review also addresses the evolving ethical and regulatory environment surrounding these influential technologies (Kumar et al., 2010). For this purpose, the paper is structured to initially introduce current issues with animal nutrition, then detail each of the main biotechnological applications, and finally conclude by drawing the conclusions, considering current limitations, and recommending exact areas for future research.

Methodology

This review was built from a systematic and exhaustive review of the scientific literature, in a attempt to provide a sound, up-to-date, and evidence-based synthesis of the subject. The research process focused on the identification and compilation of the most important and impactful available studies.

Literature selection was decided by specific modulation and exclusion standard. Inclusion criteria surrounded: (1) peer-reviewed original research articles, review articles, and meta-analyses; (2) studies published in English; and (3) articles directly relevant to the application of biotechnological tools in animal nutrition (Khan et al., 2024). Conversely, exclusion criteria comprised: (1) non-peer-reviewed sources such as conference abstracts lacking sufficient data, industry reports without clear scientific validation, and opinion pieces; (2) studies primarily focused on human nutrition without direct relevance to livestock; and (3) articles where the full text was inaccessible.

To ensure the review accurately reflects the current state of knowledge in this rapidly evolving field, a strategic timeframe for publications was adopted. While representative literature from the last two decades was incorporated to provide critical background, a particular emphasis was placed on identifying and integrating the most influential publications from 2020 up to and including 2025. This focused approach guarantees that the review reflects the latest scientific breakthroughs, emerging trends, and contemporary perspectives.

Literature Review

Current Challenges in Animal Nutrition

While widespread, traditional animal feeds present some longstanding problems that inherently constrain the sustainability and efficiency of contemporary livestock production. Firstly, there are nutritional and economic constraints of conventional feedstuffs. The livestock sector's reliance on few staple crops, mainly soybean meal and maize, exposes producers to extremely volatile prices and subjects them to human food versus feed-producing systems competition for global resources.

Besides, the nutritional potential of most plant ingredients is generally impaired by certain anti-nutritional factors (ANFs). For instance, phytate (phytic acid), a principal ANF in cereals and oilseeds, drastically depresses the digestibility of phosphorus—a mineral of paramount importance in bone growth and energy metabolism—in monogastric animals like poultry and swine. Phytate also undermines general nutrient availability via chelation with protein and other essential minerals. Similarly, non-starch polysaccharides (NSPs), fiber-like substances prevalent in the cell walls of most cereals, are poorly digested by most livestock species. These NSPs can increase intestinal viscosity, reducing the digestion and absorption of nutrients, contributing to poor gut health, and leading to issues such as wet litter in poultry production (Malešević et al., 2023).

Along with these dietary limitations, traditional feeding practice has profound environmental effects. Ruminant enteric methane (CH_4), a fermentation by-product, is a potent greenhouse gas, and the livestock industry is a significant contributor to global greenhouse gas emissions. Furthermore, inefficient dietary use of phosphorus and nitrogen leads to their excess in animal manure. This manure is a major source of environmental pollution when applied as fertilizer to land or when washed into water bodies, contributing to nitrous oxide (N_2O), another powerful greenhouse gas, and leading to the eutrophication of aquatic ecosystems (characterized by oxygen-depleting algal blooms).

Genetic Modification and Gene Editing in Feed Crops

Plant genetic modification is probably the most efficient and direct biotechnological method of remedying inherent micronutrient deficiencies in feedstuffs at source (Kumar & Sunil, 2024). Plant genetic modification has advanced significantly, from proven genetic modification (GM) techniques—which typically comprise the transfer of genes from one plant species to another—to recent advances in precision gene editing, such as CRISPR-Cas9, which enables highly specific modifications to a plant's native genetic code.

First-generation GM crops set a good example for enhancing feed quality. One major advance has been the creation of low-phytate soybeans and maize. These plants carry a gene that encodes the phytase enzyme so that monogastric animals can digest the anti-nutritional compound phytate effectively. Not only does this innovation provide animal with nutrient phosphorus and other minerals but also reduced excretion of phosphorus significantly, which relieves one of farm water pollutions (Dimas, 2022). Another successful application is in maize varieties with an improved amino acid profile, i.e., supplemented with lysine—often a limiting nutrient. This invention removed the need for expensive synthetic amino acid addition to feeding rations (Rahman et al., 2023).

The coming of gene correction, spearheaded by CRISPR-Cas9, has made plant improvement possible in a whole new world, promising unmatched speed and precision. Gene editing contrasts with traditional genetic modification (GM), in which foreign DNA is never introduced to the process but involves small, targeted modifications such as knocking out unwanted genes or switching their function. Its implications on animal nutrition are overwhelmingly vast. A cutting-edge example is ongoing research directed towards the improvement of canola (rapeseed) for animal nutrition. Scientists successfully re-engineered the rapeseed genome using CRISPR to reduce anti-nutritional factors like glucosinolates, significantly improving the quality and safety of resulting seedcake as a source of animal protein.

Global realization of the transformational power of the new technologies is growing. A novel FAO report explains the immense potential of gene editing to grow more nutritious, resilient, and sustainable crops that will shape the next-generation agrifood systems (Witten et al., 2024). With the technology now developed, it increasingly enables the rapid adaptation of crops to cater to specific nutritional requirements and adapt to evolving agricultural environments.

Enzyme Supplementation

Enzyme supplementation represents one of the most widely adopted and commercially successful applications of biotechnology in the animal feed industry. This well-established strategy involves adding specific, externally produced (exogenous) enzymes to animal diets. These enzymes function as highly specific biological catalysts, targeting and breaking down components within the feed that the animal's endogenous digestive system cannot efficiently process. By doing so, they release valuable nutrients, increase the energy value of feedstuffs, and reduce the excretion of undigested waste into the environment (Jiang et al., 2024), thereby playing a decisive role in minimizing the environmental footprint of livestock production. The most commonly utilized feed enzymes are categorized into three main groups based on their target substrate, as summarized in Table 1.

Table 1. Major classes of exogenous enzymes used in animal nutrition

Enzyme Class	**Target Substrate**	**Mechanism of Action**	**Primary Benefit(s)**
Phytases	Phytate (Phytic Acid)	Hydrolyzes phytate, releasing bound phosphorus and minerals.	Improved mineral utilization; Reduced phosphorus pollution.
Carbohydrase (e.g., Xylanase, β-glucanase)	Non-Starch Polysaccharides (NSPs)	Break down indigestible fiber, reducing gut viscosity.	Increased feed energy value; Improved gut health and litter quality.
Proteases	Proteins / Anti-nutritional proteins	Supplements the animal's endogenous enzymes to enhance protein digestion.	Better amino acid absorption; Reduced nitrogen excretion; Destruction of protein-based ANFs.

The commercial success of feed enzymes is built on three main classes, each targeting a specific anti-nutritional factor:

- **Phytases** were pioneering enzymes in this field, specifically targeting phytate, the primary storage shape of phosphorus in cultivate -based component. By breaking down the phytate molecule, phytase supplementation releases digestible phosphorus and other essential chelated minerals like calcium and zinc. This not only directly improves the animal's nutritional status but also provides a critical environmental benefit by significantly reducing phosphorus runoff from manure, a major cause of water pollution.
- **Carbo hydrases**, a diverse group of enzymes including xylanases and β-glucanases, are designed to break down complex non-starch polysaccharides (NSPs) establish in the cell dike of cereal petite like corn, barley, and rye. These NSPs are largely indigestible and can increase the viscidity of intestinal contacts, which impairs overall nutrient absorption. By dismantling these complex carbohydrates, carbo hydrases reduce gut viscosity, improve energy utilization, and help maintain a healthier gut environment (Wu, 2024).
- **Proteases** supplement the animal's endogenous protein-digesting enzymes (e.g., trypsin and pepsin) to enhance the breakdown of dietary proteins. This is especially beneficial for young animals with immature digestive systems or when utilizing alternative protein sources that may exhibit lower digestibility. Improved protein digestion results in better amino acid availability for growth and reduces the excretion of undigested nitrogen, which is another environmental concern**.**

While these enzymes are now standard in the industry, the field continues to evolve. Current research focuses on discovering novel enzymes with unique capabilities, enhancing the thermal stability of existing enzymes to withstand the heat of feed manufacturing, and developing sophisticated multi-enzyme "cocktails." These advanced formulations are designed to target the complex array of substrates in modern, diverse diets, further unlocking the nutritional potential of feed ingredients and enhancing the sustainability of animal production (Asghar et al., 2024).

Probiotics and Prebiotics

Apart from modifying the feed itself, biotechnology provides powerful tools to directly and positively affect the microbial gut ecosystem of the animal. Often described as the gut microbiota, the intricate population of microorganism functions as an organ and plays a crucial role in immune system development, digestion, nutrient synthesis, and protection against pathogens (Swanson et al., 2025). Adjusting the microbiota with functional ingredients like probiotics and prebiotics has become a significant aspect of contemporary animal nutrition strategies during the period of decreased antibiotic use (Sharma & Subramanian, 2025).

Probiotics are live bacteria that, when provided in sufficient quantities, offer health benefits to the host (Swanson et al., 2025). The live bacteria, typically Lactobacillus, Bifidobacterium, Bacillus, or yeast Saccharomyces cerevisiae, are supplemented in the feed to establish a beneficial microbial balance. Their mechanisms of action are multifaceted; they include competitive exclusion, in which they compete with the pathogen for attachment sites and nutrients on the intestinal wall; the offspring of antimicrobial metabolites such organic acids and bacteriocins that inhibit pathogen growth; and manipulation of the host immune system via interaction with a gut-associated lymphoid tarpaulin (GALT).

Prebiotics are indigestible feed elements that provide the host's natural beneficial bacteria with a specific food source. They "selectively promote the growth and/or function of a few types of bacteria in the the intestines and thus enhance host health," according to Gibson & Roberfroid (Yoo et al., 2024). Mannan-oligosaccharides (MOS) and fructo-oligosaccharides (FOS) are frequent examples. By nourishing beneficial populations like bifidobacteria, prebiotics indirectly help to suppress harmful microbes. Products that strategically combine both probiotics and prebiotics are known as **syn biotics**, aiming for a synergistic effect that is greater than either component alone.

which is designed to have a synergistic effect on gut health. To clearly delineate the differences between these two important functional ingredients, Table 2 provides a direct comparison.

Table 2: Comparison of probiotics and prebiotics in animal nutrition

Feature	**Probiotics**	**Prebiotics**
Definition	Live, beneficial microorganisms that confer a health benefit.	**Non-digestible feed ingredients that selectively feed beneficial bacteria.**
Type	Live bacteria (e.g., Lactobacillus, Bacillus) or yeast.	**Soluble fibers (e.g., Fructo-oligosaccharides [FOS], Mannan-oligosaccharides [MOS]).**
Mechanism	Competitive exclusion, immune modulation, production of antimicrobial compounds.	**Serves as a substrate for beneficial native gut bacteria, promoting their growth.**
Primary Goal	To introduce beneficial microbes directly into the gut ecosystem.	**To support and enhance the growth of existing beneficial microbes.**

The research and application in this field are rapidly advancing. The focus is shifting from using generic microbial strains to identifying and developing "next-generation probiotics" with specific, scientifically validated functionalities. Current trends emphasize a deeper understanding of the precise mechanisms of action and the complex interactions between the host, its diet, and the specific microbial strains being administered. This data-driven approach aims to move towards more predictable and effective applications tailored to specific challenges, with poultry nutrition being a particularly active area of research for future perspectives [(Gao et al., 2025).

Rumen Microbiome Modulation

In cattle and other ruminant animals, sheep, and goats, digestion is fundamentally various of the monogastric animals, revolving around the vast and complex microbial ecosystem housed within the rumen. Billions of bacteria, protozoa, fungus, and archaea are present in this sizable fermentation chamber, and they cooperate to break down fibrous plant components like cellulose and hemicellulose that are indigestible to the majority of other animals. With two main strategic objectives, improving digestive productivity and efficiency and reducing the environmental impact of ruminant production—biotechnology presents special opportunities to modify this rumen microbiome (García-Rodríguez et al., 2020)

Enteric methane (CH4) production minimization is among the primary goals of rumen modulation. Up to 12% of the animal's diet energy is lost in methane production, a powerful greenhouse gas. Among the biotechnological approaches to this is through the use of certain feed additives, including oils, nitrates, and plant extracts, that can suppress the bounce of methanogens—microbes accountable for the offspring of methane. Use of direct fed microbials (DFMs), such as strains of bacteria and yeast, which can alter fermentation pathways for increased efficiency and reduction in methanogenesis is also becoming popular.

The other primary goal is to improve the efficiency of fiber digestion (fibrolysis). By enhancing the ability of the rumen microbiome to break down tough forages, more energy and nutrients can be extracted from the same amount of feed, improving the animal's feed conversion ratio. This can be achieved by supplementing the diet with fibrolytic enzymes (e.g., cellulases and xylanases) or by introducing superior fiber-digesting microorganisms.

The advent of "omics" technologies (genomics, proteomics, metabolomics) has revolutionized this field. These technologies open the door for studying the rumen ecosystem with a level of depth not previously possible, elucidating prominent microbial players and their metabolic functions. Current reviews emphasize that such detailed information on microbial communities is the greatest prerequisite for designing effective and targeted manipulation strategies. An important step towards sustainable livestock production, this information-led approach opens the door to a new generation of feed additives and management practices capable of optimizing rumen function to realize maximum productivity at low environmental cost (Sandhu et al., 2025).

Socioeconomic and Ethical Considerations

The use of biotechnology in animal nutrition is not a technical issue; it is integrally associated with a mix of socioeconomic considerations, opinion, and ethics. To navigate this environment is as much an issue of use for the appropriate and effective utilization of these potent tools as scientific verification.

An important lesson can be learned from the history of first-generation genetically modified (GM) plants. Though there is an almost uniform agreement among scientists that approved genetically modified products are safe, consumer scepticism and public apprehension have been major obstacles in the majority of places in the world (Driscoll & Edwards, 2024). As a result, mandatory labelling laws and complex, strict, and very often expensive regulatory systems have been established. These rules have the potential to be barriers to trade and can undermine the introduction of useful technologies, especially for small developers and farmers, even though they are designed to promote consumer safety and choice.

With new technologies arising, including gene editing, the argument is now changing quickly. Current paradigms of governance are challenged by technologies such as CRISPR-Cas9, which allow precise gene modification without the addition of extraneous DNA. Whether they should be regulated as heavily as conventional GMOs has been put into question through this global discourse. Gene editing has a huge promise for agrifood systems, but it is observed that even the world's major organizations like FAO believe in its huge promise and at the same time emphasize the necessity of having effective governance and public discourse to regulate its use responsibly (Jha & Mishra, 2021). When technology is applied to the animals themselves rather than specifically for feeding, the challenge increases manifold. Genetically altered livestock also have a lengthy, difficult, and uncertain path to regulatory approval and consumer acceptance, full of huge ethical and social hurdles (Adebiyi & Adebiyi, 2023).

Beyond regulation, persistent ethical questions remain. A central concern is animal welfare. While biotechnology can be used to improve animal health, critics question whether the primary driver is to push animals beyond their natural physiological limits solely for increased productivity. Furthermore, questions of economic equity are paramount. There is concern that the benefits of these high-cost, often patented, technologies may flow primarily to large multinational corporations, potentially disadvantaging small-scale farmers and widening the gap in global agriculture. Addressing these issues requires a sustained and transparent dialogue among scientists, policymakers, farmers, and the public to foster confidence and guarantee that these developments support a more just and moral food system.

Synthesis and Critical Discussion

The preceding sections have systematically illustrated that the modern biotechnological toolkit offers a sophisticated and multi-pronged response to the core challenges of animal nutrition. It is no longer a matter of single solutions but of a comprehensive portfolio. The dual genetic approaches of established GM technology and newer, precise gene-editing tools provide powerful ways to redesign feedstuffs from the ground up, tackling anti-nutritional factors and enhancing nutrient profiles at their source [9, 22, 23]. This is complemented by a "post-harvest" strategy using an ever-improving arsenal of exogenous enzymes that unlock the full potential of feed ingredients (Van Eenennaam et al., 2021). Concurrently, a deeper understanding of animal physiology is addressed through targeted microbiome modulation, whether via next-generation probiotics to bolster gut health in monogastrics or advanced strategies to optimize the complex fermentation processes in the rumen (Patra & Park, 2022).

A critical discussion of this landscape reveals that the most significant future gains will likely come from synergistic and integrated approaches rather than the isolated use of these technologies. One can envision a highly integrated system where an animal is fed a diet containing a gene-edited crop with enhanced fiber digestibility (Moss, 2025).

This diet could be supplemented with a bespoke enzyme cocktail designed to work specifically on that crop's unique carbohydrate structures. The breakdown products from this enzymatic action could then serve as ideal prebiotics, fostering the colonization and activity of a co-administered, next-generation probiotic strain selected for its ability to produce beneficial short-chain fatty acids (Gao et al., 2022). This multi-layered strategy, where each technology enhances the efficacy of the others, represents the true frontier of advanced animal nutrition.

However, the increasing sophistication of these tools demands an equally sophisticated application. The "one-size-fits-all" model is obsolete. The efficacy of any biotechnological intervention is highly context-dependent, influenced by the animal's own genetics, its baseline gut microbiome, the precise composition of its diet, and the specific stressors of its environment. Therefore, the critical challenge for the future is not just the development of new technologies, but the development of diagnostic and decision-support systems that allow for their precise deployment. This involves leveraging data from genomics, feed analysis, and microbiome sequencing to tailor nutritional strategies to specific animals or herds, ensuring that the right tool is used at the right time for maximum impact and return on investment. Table 3 showed an outline of the key nutritional defy discussed and their corresponding biotechnological solutions.

Table 3: Biotechnological Solutions to Key Challenges in Animal Nutrition

Challenge	**Biotechnological Solution(s)**
Poor Phosphorus Utilization (due to Phytate)	Phytase enzymes; Low-phytate GM/GE crops.
Indigestible Fiber (NSPs in cereals)	Carbohydrase enzymes (Xylanase, β-glucanase).
Gut Health & Pathogen Control (Post-AGPs)	Probiotics; Prebiotics; Synbiotics.
Ruminant Methane Emissions	Rumen microbiome modulators; Direct-fed microbials (DFMs); Specific inhibitors.
Poor Protein Quality (Limiting Amino Acids)	High-lysine GM/GE crops; Protease enzymes.

Conclusion

In conclusion, this review systematically establishes that modern biotechnology has transitioned from a peripheral tool to a central and indispensable force in shaping the future of animal nutrition. Our findings demonstrate a clear technological evolution from broad-spectrum interventions to highly precise applications. The combined power of established genetic modification, cutting-edge gene editing, next-generation microbial additives, and sophisticated enzyme formulations provides a robust toolkit to address the industry's most pressing issues. These technologies offer tangible pathways to enhance nutrient utilization, mitigate environmental impact, and maintain animal health in the absence of antibiotic growth promoters, thereby supporting the dual goals of productivity and sustainability.

Despite this remarkable progress, critical limitations and knowledge gaps persist. While genome editing now offers incredible precision, our understanding of the complex, downstream effects on the whole organism and the broader ecosystem remains incomplete. The intricate host-microbiome dialogue is still being deciphered, leading to sometimes variable outcomes from microbial interventions. Quite possibly the most significant current constraint is the disparity between the rapidly increasing pace of scientific discovery and the much slower rate of adaptation and social acceptance in regulation, a problem underlined by global controversy surrounding gene editing and genetically modified animals.

To get through this future successfully, a clear and directed research agenda is necessary. Future research priorities must include:

- Accelerating the deployment of gene-editing technologies like CRISPR to develop feed crops with stacked traits, such as concurrent high digestibility, enhanced nutrient profile, and climate resistance.
- Developing the next generation of precision microbiome engineering, which extends beyond general probiotics to design host-specific microbial consortia with defined, predictable functionalities.
- Conducting systems-level research to evaluate the synergy of combining these multiple technologies (e.g., a gene-edited feed and customized enzyme and probiotic package).
- Focusing on socio-ethical and regulatory science investments aimed at developing adaptive governance models for emerging technologies and promoting open, evidence-based public discussion.

By advancing on these areas in a responsible manner, the potential of biotechnology can be best harnessed. This will be vital in steering the world's livestock sector to a future that is not just more productive and efficient but more possible and more ethically sound, capable of responding to the food security requirements of an increasing global population.

Conflict of Interest

The authors declare that they have no competing interests**.**

Author Contributions

All authors' contributions are equal for the preparation of research in the manuscript.

References

Adebiyi, O. A., & Adebiyi, F. G. (2023). Unlocking the potentials of feed enzymes in animal nutrition: a review. *Applied Tropical Agriculture, 2*8(2), 1-10.

Asghar MU, Sajid QU, Wilk M, Konkol D, Korczyński M. Influence of various methods of processing soybeans on protein digestibility and reduction of nitrogen deposits in the natural environment–a review. *Annals of Animal Science*. 2024 Oct 1;24(4):1037-49.

Canton, H. (2021). Food and agriculture organization of the United Nations—FAO. In The Europa directory of international organizations 2021 (pp. 297-305). Routledge.Urgessa, O. E., Koyamo, R., Dinka, H., Tefese, K., & Gemeda, M. T. (2024). Review on desirable microbial phytases as a poultry feed additive: their sources, production, enzymatic evaluation, market size, and regulation. *International Journal of Microbiology, 2*024(1), 9400374. https://doi.org/10.1155/2024/9400374.

Charitos, I. A., Colella, M., Carretta, D. M., & Santacroce, L. (2025). Probiotics, gut microbiota and physical activity: *A close relationship. Sports Medicine and Health Science.* https://doi.org/10.1016/j.smhs.2025.04.003.

Dimas, A. T. (2022). *Evaluation of Corn Expressed Glucanase and High and Low Specific Activity Corn Expressed Phytase at Different Inclusion Rates on Growth Performance of Broilers Fed Corn-Soybean Meal Based Diets* (Doctoral dissertation).

Driscoll, A., & Edwards, B. (2024). Concentrated Animal Feeding Operations. *In Encyclopedia of Technological Hazards and Disasters in the Social Sciences* (pp. 152-158). Edward Elgar Publishing. https://doi.org/10.4337/9781800882201.ch24.

Gao, C., Kikulwe, E. M., Kuzma, J., Lema, M., Lidder, P., Robinson, J., ... & Zhao, K. (2022). *Gene editing and agrifood systems.* https://doi.org/10.4060/cc3579en.

Gao, Y., Li, Z., Hong, S., Yu, L., Li, S., Wei, J., ... & Wang, X. (2025). *Recent stabilization of agricultural non-CO2 greenhouse gas emissions in China*. National Science Review, 12(4), nwaf040. https://doi.org/10.1093/nsr/nwaf040.

García-Rodríguez, J., Mateos, I., Saro, C., González, J. S., Carro, M. D., & Ranilla, M. J. (2020). Replacing forage by crude olive cake in a dairy sheep diet: *Effects on ruminal fermentation and microbial populations in rusitec fermenters. Animals, 1*0(12), 2235. https://doi.org/10.3390/ani10122235.

Jha, R., & Mishra, P. (2021). Dietary fiber in poultry nutrition and their effects on nutrient utilization, performance, gut health, and on the environment: a review. *Journal of Animal Science and Biotechnology, 1*2(1), 51.

Jiang, Z., Mei, L., Li, Y., Guo, Y., Yang, B., Huang, Z., & Li, Y. (2024). *Enzymatic regulation of the gut microbiota: mechanisms and implications for host health. Biomolecules*, 14(12), 1638. https://doi.org/10.3390/biom14121638.

Kapoor, T., Kansal, A., Mohamed Jaffar, A., Venkatesan, D., Sarmah, R. G., Renuka Jyothi, R., & Verma, S. (2025). Nutritional innovations in aquafeed for sustainable and eco-friendly fish farming. *International Journal of Aquatic Research and Environmental Studies, 5*(1), 685–695. https://doi.org/10.70102/IJARES/V5I1/5-1-61

Khan, A., Qadeer, A., Wajid, A., Ullah, Q., Rahman, S. U., Ullah, K., ... & Horky, P. (2024). Microplastics in animal nutrition: Occurrence, spread, and hazard in animals. *Journal of Agriculture and Food Research, 1*7, 101258.https://doi.org/10.1016/j.jafr.2024.101258.

Kumar, R. B., & Sunil, K. (2024). Biotechnological Approaches to Develop Personalized Medicines for Rare Genetic Disorders. *Clinical Journal for Medicine, Health and Pharmacy, 2*(2), 20-28.

Kumar, V., Sinha, A. K., Makkar, H. P., & Becker, K. (2010). *Dietary roles of phytate and phytase in human nutrition: A review. Food chemistry, 1*20(4), 945-959. https://doi.org/10.1016/j.foodchem.2009.11.052.

Malešević, Z., Govedarica-Lučić, A., Bošković, I., Petković, M., Đukić, D., & Đurović, V. (2023). *Influence of different nutrient sources and genotypes on the chemical quality and yield of lettuce.*

Martin, G. B. (2024). Perspective: science and the future of livestock industries. *Frontiers in Veterinary Science, 1*1, 1359247.https://doi.org/10.3389/fvets.2024.1359247.

Mehrani, M. J., Tashayoei, M. R., Ferdowsi, A., & Hashemi, H. (2016). Qualitative evaluation of antibiotics in WWTP and review of some antibiotics removal methods. *International Academic Journal of Science and Engineering, 3*(2), 11-22.

Menon, R., & Joshi, A. (2024). Enzyme Recovery and Reuse via Ultrafiltration in Dairy Processing. *Engineering Perspectives in Filtration and Separation, 1*-4.

Moss, O. (2025). Enhancing rapeseed seedcake quality for feed and food using CRISPR-Cas RNP gene editing. *Acta Universitatis Agriculturae Sueciae*, (2025: 24). https://doi.org/10.54612/a.1dk92laqgh.

Patra, A. K., & Park, T. (2022). Rumen microbiome and its manipulation for improving ruminant production. *Animals, 1*2(15), 1895.

Rahman, Saleem Ur, Evan McCoy, Ghulam Raza, Zahir Ali, Shahid Mansoor, and Imran Amin. "Improvement of soybean; A way forward transition from genetic engineering to new plant breeding technologies." *Molecular Biotechnology 6*5, no. 2 (2023): 162-180.

Said, S., Agung, P. P., Putra, W. P. B., & Kaiin, E. M. (2020, April). The role of biotechnology in animal production. In IOP Conference Series: *Earth and Environmental Science* (Vol. 492, No. 1, p. 012035). IOP Publishing.

Sandhu, R., Chaudhary, N., Shams, R., & Dash, K. K. (2025). Genetically modified crops and sustainable development: navigating challenges and opportunities. *Food Science and Biotechnology, 3*4(2), 307-323.

Sharma, P., & Subramanian, K. (2025). Molecular Mechanisms of Antibiotic Resistance in Bacteria. In *Medxplore: Frontiers in Medical Science* (pp. 19-36). Periodic Series in Multidisciplinary Studies.

Swanson, K. S., Allenspach, K., Amos, G., Auchtung, T. A., Bassett, S. A., Bjørnvad, C. R., ... & Fahey Jr, G. C. (2025). Use of biotics in animals: impact on nutrition, health, and food production. *Journal of Animal Science, 1*03, skaf061. https://doi.org/10.1093/jas/skaf061.

Van Eenennaam, A. L., De Figueiredo Silva, F., Trott, J. F., & Zilberman, D. (2021). Genetic engineering of livestock: the opportunity cost of regulatory delay. *Annual Review of Animal Biosciences, 9*(1), 453-478. https://doi.org/10.1146/annurev-animal-061220-023052.

Witten, S., Werner, D., Veit, C., Schubbert, A., Kölln, M., Kluess, J., ... & Aulrich, K. (2024). Supply of protein feed to young pigs and chickens in organic farming (No. 240a). *Thünen Working Paper*. https:// doi:10.3220/WP1715760422000

Wu, S. B. (2024). Advancements in animal nutrition: The interplay of feed enzymes, gut health, and nutrient supply in poultry and pig production–A tribute to Professor Mingan Choct's 30-year scientific legacy. *Animal Nutrition, 17*, 373. https:// doi: 10.1016/j.aninu.2024.03.002.

Yoo, S., Jung, S. C., Kwak, K., & Kim, J. S. (2024). The role of prebiotics in modulating gut microbiota: implications for human health. *International Journal of Molecular Sciences, 25*(9), 4834. https://doi.org/10.3390/ijms25094834.